

Appendix J

57-20
N92-10051⁴⁰⁰⁵³
p. 20

Department of Aeronautical and Astronautical Engineering
The Ohio State University

MAGNETOPLASMA DYNAMIC ARCJET RESEARCH

OM 500208

MPD THRUSTER RESEARCH ISSUES, ACTIVITIES, STRATEGIES

Briefing at MPD Thruster Technology Workshop

16 May 1991

Washington, DC

Department of Aeronautical and Astronautical Engineering
The Ohio State University

MAGNETOPLASMA DYNAMIC ARCJET RESEARCH

BRIEFING OUTLINE

RESEARCH ISSUES

- What are the development "opportunities" available to the MPD thruster for application to missions over the next decades?
- What's different compared to twenty years ago?
- How should we be approaching MPD thruster development?

RESEARCH ACTIVITIES IN THE OSU AAE DEPARTMENT

- What is happening now?
- What is becoming available?

RESEARCH STRATEGIES

- How do we safeguard an evolutionary program that can provide continual contributions to space activities, while responding to opportunities for an accelerated national commitment to space exploration?

MPD THRUSTER RESEARCH ISSUES

EFFICIENCY

- Promise of MPD thruster is that it is a very robust system that can handle high power levels, while delivering high specific impulse. This does not relieve it of a cost-per-ion efficiency penalty at lower specific impulse values. The robustness of an MPD thruster compared to an electrostatic device derives fundamentally from the use of Hall electric fields instead of accelerating grids.
- Any process that requires more energy per ion than the minimum value can be regarded as an inefficiency of the ionized-propellant system (including the electron flow needed to neutralize the propellant). In MPD vs electrostatic thrusters, the ion source and neutralizer are presently coupled very closely to the accelerator system. We have historically accepted the gas discharge and electrode processes provided by particular devices, and pressed on with performance studies.
- An additional efficiency factor that has received inadequate attention is simply the directedness of the exhaust flow. There are two considerations here: direction of the accelerating force field, (akin to concern for beam optics in electrostatic thrusters); and collimation of the exhaust flow, including the notion of obtaining additional thrust kinetic energy from plasma internal and/or rotational energy.

MPD THRUSTER RESEARCH ISSUES (continued)

HIGH SPECIFIC IMPULSE

- The principal concerns here involve the possible limitation of practical specific impulse due to the "onset" of difficulties in the MPD thruster. These difficulties include, to varying degrees in different devices: increased frozen-flow loss, and increased losses at the anode, the cathode, and insulator surfaces. The latter category of losses also afflict the thruster in terms of lifetime and thermal management.
- There are many theories providing explanations for "onset". A reasonably common element in these theories is the association of higher specific impulse with lower particle densities in the MPD discharge. At lower densities, the discharge is:
 - a) Depleted of sufficient charge-carriers near an electrode, leading either to sheath or hydrodynamic instabilities;
 - b) Depleted of sufficient charge-carriers within the plasma, permitting the growth of various drift instabilities;
 - c) Deprived of sufficient energy sinks to absorb, in a uniform manner, the dissipation demanded by steady, electromagnetic acceleration.
- While "onset" can adversely affect the efficiency and lifetime of MPD thrusters, the momentum equation for electromagnetic acceleration must still be satisfied. Deviations from expected performance in terms of thrust and/or exhaust speed must be examined, particularly at low densities, for the effects of viscous drag, and mass addition (associated with "onset" processes); an additional concern is gross distortion of the discharge pattern, e.g., spoking or filamentation.

MPD THRUSTER RESEARCH ISSUES (continued)

LIFETIME AND SYSTEM PERFORMANCE

- Inefficiencies injure thruster performance in three ways: increased power system to obtain the desired output; increased thermal management to handle loss; and reduced component lifetime.
- It is a system issue to select the optimum operating values for intensive properties, such as current density, traded against component efficiencies and lifetimes. Research/development tasks and system designs must be consistent. To provide input to system trades, component development and lifetests are, therefore, very important (even if we still prefer, and require, full system tests in an accurate environment).

MPD THRUSTER OPPORTUNITIES

BASIC APPROACH

IF YOU DON'T LIKE IT, FIX IT !

- Theories indicate that there are physical causes for difficulties in MPD thrusters. They also imply solutions based on proper choices of operating regime and device geometry. We must be prepared to change geometric arrangements as we change terminal properties. This includes adjusting the relative magnitudes and directions of applied and self-magnetic fields.
- Some components, such as electrodes, may never perform adequately while incorporated automatically as part of the main thruster flow channel. We need to invent components that satisfy their special performance requirements. (We didn't require the ion source in an electrostatic thruster to be a flat plate, so why must the cathode be a simple, solid cylinder?)

MPD THRUSTER OPPORTUNITIES (continued)

BRIEF EXAMPLES OF DIRECTIONS FOR DEVELOPMENT

Overcoming "Onset"

Principal difficulty may derive from excess dissipation deposited in too few particles. Solution lies in minimizing dissipation per unit volume, i.e., lowering the current density and increasing the particle density.

For constant area channels at high magnetic Reynolds number, the thickness of the current conduction zone scales as;

$$d = 1/\sigma \mu u ,$$

where σ = electrical conductivity
and u = flow speed

Typically, microturbulence becomes important when the drift speed for the electrons, carrying the current, exceeds some speed, such as the ion thermal speed. In terms of the total current J and mass flow rate \dot{m} , the electron drift speed scales as:

$$v_{de} = K J / n_e e (2 \pi r d)$$

$$= K \sigma u^2 J h / \dot{m} ,$$

where K = a scaling constant
 n_e = electron density
 r = channel radius
and h = channel height

MPD THRUSTER OPPORTUNITIES (continued)

Overcoming "Onset" (continued)

If the flow speed is determined by the electromagnetic thrust, so $u = g J^2 / \dot{m}$, then:

$$\begin{aligned} v_{de} &= K \sigma u^3 h / g J \\ &= K \sigma h g^2 J^5 / \dot{m}^3 , \end{aligned}$$

This suggests that, while we should expect microturbulence to be more important at higher specific impulse, we can mitigate the situation by increasing the current at the desired exhaust speed. Narrower channels also improve the flow by increasing the mass density at a given flow rate.

Furthermore, it should be noted that the scaling of current conduction thickness with magnetic Reynolds number did not account for varying channel height, which can reduce the current density considerably, thereby decreasing the required drift speed.

MPD THRUSTER OPPORTUNITIES (continued)

BRIEF EXAMPLES OF DEVELOPMENT DIRECTIONS

Improving Electrode Performance

Hollow Cathode vs Solid Cathode:

It has been a reasonable notion for some time that the performance of a cathode could be improved considerably if we could control the environment of the cathode, rather than merely submit it to the bombardment of whatever flow field and species were provided by the thruster channel itself. This notion, while seductive, has tended to founder on our inability to predict and design hollow cathodes that actually function as such over all ranges of desired operation. For example, the simple interplay of cathode fall voltage and a resistive voltage drop of comparable magnitude within the hollow cathode can preclude significant incursion of the current. Theory indicates, however, that proper operation can be obtained by varying the scale size, while matching the current and mass flow rate. Successful operation would offer the opportunity to increase the available emission area, while maintaining the effective cathode radius, and also to reduce losses due to processes such as evaporation and plasma radiation.

Anode Shaping:

Historically, we have measured and accepted the current density, and associated flow pattern, in the vicinity of the anode. Yet, we may expect for a magnetized plasma flow at high magnetic Reynolds number that two-dimensional expansion at the exit of the thruster will result in current concentration at the anode lip. Such concentration, combined with reduced particle density, may result in plasma processes that enhance losses near the anode. Furthermore, the rather abrupt expansion presently available to the magnetized plasma flow provides a significant non-axial component to the exhaust flow. It should be possible to design the anode shape, both to ameliorate problems associated with current concentration, and to improve the thrust efficiency in terms of flow direction.

MPD THRUSTER OPPORTUNITIES (continued)

BRIEF EXAMPLES OF DEVELOPMENT DIRECTIONS

Applied Fields to the Rescue

Applied fields are not a panacea, but they are not anathema either.

Impedance Enhancement:

At lower power levels, the back EMF available in self-field MPD thrusters is simply too small to compete effectively with the voltage drops required near electrodes, so the efficiency will automatically suffer. Addition of a solenoidal field (rz-plane) provides several mechanisms that can increase the voltage across the plasma, including Hall electron flow (increases resistance), plasma rotation (homopolar motor), and direct interaction of discharge or induced currents with applied field components (linear motors). At fixed total power, while the efficiency may improve with higher discharge voltage, the total current must decrease, resulting in insufficient current density to achieve diffuse discharge.

Discharge Control:

By shifting the direction of net current flow, the addition of solenoidal fields can alter the physical scale lengths associated with dominant modes of some plasma instabilities, and perhaps create sufficient "shear" for actual stabilization. Often, however, the plasma simply becomes unstable in other directions. An increase in azimuthal current density (Hall current), for example, again offers the opportunity for drift instabilities. If we have too much dissipation chasing too few particles, without other mechanisms (e.g., heat transfer) available to diffuse this energy, we can have instability growth. ('Inflation economics for plasma electrons').

In the simplest notion, the applied field "swirls" the plasma to smoothen out nonuniformities (especially near electrodes. Azimuthal variations have nevertheless been observed in some devices.

MPD THRUSTER OPPORTUNITIES (continued)

Applied fields (continued)

Flow Control:

Solenoidal fields can be used to guide the flow, in the manner of a solid nozzle, and thereby improve thrust efficiency simply by achieving more collimation. In principle, the proper variation of applied field with position can also contribute to control of the current distributions on electrodes. There is also the possibility of converting plasma rotational energy and internal energy to thrust energy. For a fluid plasma, the control of the flow, including energy conversion, is accomplished through pressure gradients, so we must be careful not to lose energy via internal states in a hypersonic flow interaction. For a collisionless plasma, the behavior is more complicated, including non-adiabatic transitions and cross field drifts.

MPD THRUSTER OPPORTUNITIES

WHAT'S DIFFERENT COMPARED TO TWENTY YEARS AGO ?

- Computational fluid dynamics has finally penetrated to the MPD thruster community.

We can now do the arithmetic for two (and a half) dimensional electromagnetically-accelerated plasma flows. This permits us to examine concepts, design experiments, and interpret data (including interpolation between regions of available measurement, and inference of quantities we couldn't measure). We can also use experimentally validated computational tools to provide scaling relations for component and system development.

- Computer-assisted diagnostics allow us to gather and manipulate data that the plasma has always offered but that has required too much effort to convert to physically-useful information, (e.g., spectral lineshapes for velocity distributions).

- We've been around the block before.

RESEARCH ACTIVITIES IN THE OSU AAE DEPARTMENT

WHAT'S HAPPENING NOW ?

Magnetic nozzles, Hollow cathodes, Anodes, Plasma studies

<u>Support</u>	<u>Student</u>	<u>Activity</u>
AAE	H. Kamhawi	Construction of high power facility; high power, applied field studies.
NASA LeRC AFOSR	N. Kiristis	Thomson scattering in magnetic nozzle exhaust; laser interferometry.
AAE	K. Li	Construction of high power facility; high power, applied field studies.
NASA LeRC AAE	P. Mikellides	Numerical computation of MPD and magnetic nozzle flows; non-equilibrium plasma flows.
AAE	A. Salhi	Theoretical and experimental electrode studies; hollow cathodes.
AAE	T. Shannon	Experimental modeling of space plasma environment.
NASA LeRC	G. Soulas	Magnetic nozzle effects on a scaled MPD thruster.
NASA LeRC	T. Umeki	Spectroscopic analysis of magnetic nozzle flows; electrode heat transfer.

RESEARCH IN THE OSU AAE DEPARTMENT

FACILITIES AND APPARATUS

WHAT'S THERE NOW ?

- Plasma sources: Quarter-scale MPD thruster, Ablative thruster
Space physics source.
- Power sources: Thruster PFN (2.3 kA, 300 usec)
Nozzle PFN (2.7 kA, 500 usec).
- Diagnostics: Electrostatic and magnetic probes,
Laser scattering - Ruby (10 J)
- Glass (60 J)
Laser interferometry and long wavelength
scattering - CO₂ (60 w)
Spectroscopy (0.25 and 0.5 m).

WHAT'S BECOMING AVAILABLE ?

- ```
-- Very high power facility ("Godzilla")
 400 kA, 2 msec (from a 5 MJ capacitor bank PFN)
-- High power, steady arcjet
 1 Megawatt, 60 sec burst-mode operation
 (presently running on air at 10 atm)
```

## RESEARCH IN THE OSU AAE DEPARTMENT

### WHAT'S HAPPENING NOW ?

- MACH2 computer code being transferred from Phillips Lab (Albuquerque) to Cray-2 at NASA LeRC.

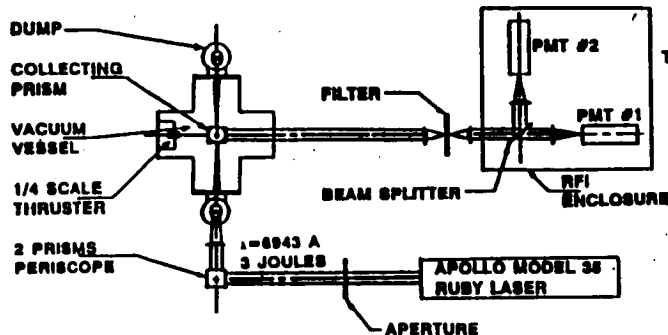
MACH2 is a 2-1/2 dimensional (includes axisymmetric rotation), MHD code developed originally to model very high power (1-100 Tw) plasma accelerators at the Air Force Weapons Lab (now Phillips Lab). The code employs an ALE procedure with a convenient block-based computational grid to handle complex flow geometries. MACH2 uses a variety of equation of state packages, such as the LANL SESAME tables, and, more recently, nonequilibrium models allowing separate constituent temperatures. It also includes phenomenological models for anomalous transport based on microturbulence. Both self-field and applied fields are treated.

MACH2 has successfully modeled the plasma flow switch experiments at AFWL, and very low density, plasma switching in particle-beam diodes at Sandia Labs. It has also recently been applied to self-field MPD thruster experiments at R & D Associates. Presently at Phillips Lab, MACH2 is being used to model compact toroid experiments.

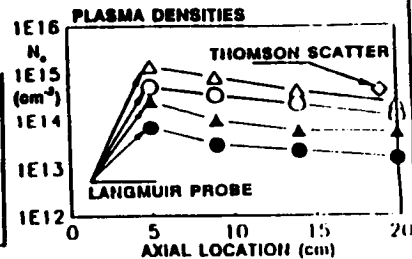
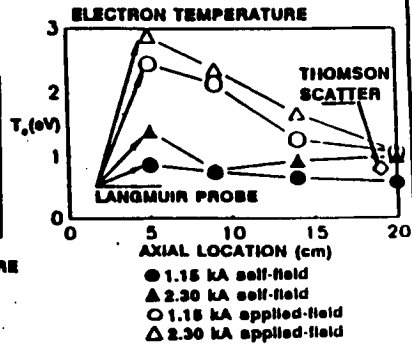
We will be working to make MACH2 an effective tool for MPD thruster development. This effort includes addition of appropriate "wall physics" and plasma modeling to compare with experimental results, in particular, the data base on applied-field thrusters generated at NASA LeRC, and magnetic nozzles at OSU. With validation, the code should be a useful contribution to the entire MPD thruster community.

## ADVANCED PROPULSION TECHNOLOGY (OSU) MAGNETIC NOZZLE RESEARCH AND TECHNOLOGY

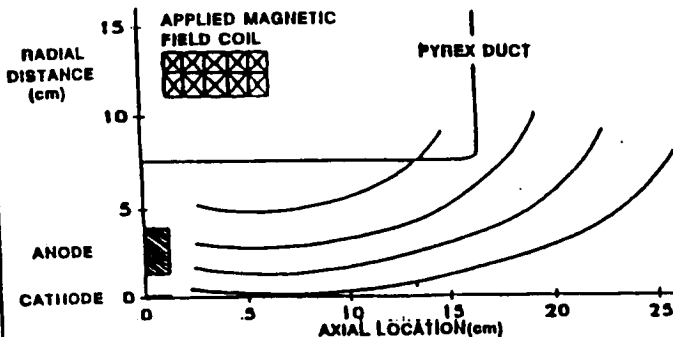
THOMSON SCATTERING SCHEMATIC LAYOUT:



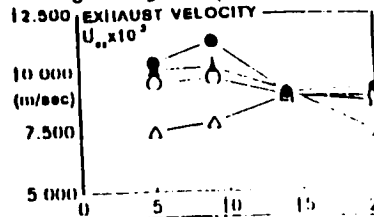
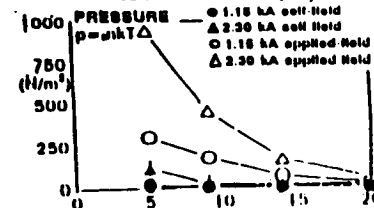
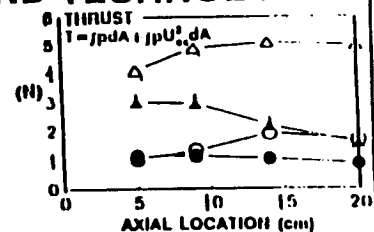
- Proof-of-Principle Thomson Scatter measurements (non-intrusive, not B-Field sensitive) successfully carried out for first time.
- Thomson Scatter results at 2.3 kA, applied B agree with Langmuir results corrected for thick sheath and B Field.



## ADVANCED PROPULSION TECHNOLOGY (OSU) MAGNETIC NOZZLE RESEARCH AND TECHNOLOGY



- Self-Field plasma expands to low pressure in 5 cm (plasma is lost). Applied-field plasma expansion is controlled and has large  $\text{spA}$  thrust.
- Applied fields can be optimized for  $U_{ex}$  max or high thrust with low  $U_{ex}$ . This will allow optimization of  $U_{ex}$  for mission requirements.





## RESEARCH STRATEGIES

HOW DO WE SAFEGUARD THE EVOLUTIONARY DEVELOPMENT OF MPD THRUSTERS,  
WHILE RESPONDING TO NATIONAL INITIATIVE FOR SPACE EXPLORATION ?

- Let's recognize the danger of debauching technology development programs that can contribute to near term, lower power missions (consistent with near term power sources), to develop the fully demonstrated capability for high power missions.
- Similarly, let's recognize that without some adequate promise of thruster performance at high powers, we may never (in our lifetimes) see the space-power systems needed for high energy missions. The driver is thrust power, not power on station, so the only incentive for developing high powers (>10's-100's of Mw) in space is the enabling interest of the thruster.
- Furthermore, since the task of developing the desired space-power system is quite formidable, and therefore expensive, we cannot ignore those moments when the national will may support the cost. (In 1960, if we had turned from manned space exploration, because system studies indicated there was no real technical advantage, then Apollo would not have occurred, and there probably would not have been a significant space program.)

## RESEARCH STRATEGIES

### HOW DO WE PROCEED ?

- The principal driver is the expected funding profile. For a major new initiative that will be sustained into the out-years, there is a challenge to ramp-up to spend the available resources. We would probably not shrink from such a challenge. Some money would be wasted, but we could envision a forced development march that would tackle problems at high power, and answer questions as they manifested themselves in melted electrodes or tanks.
- Within a more realistic funding scenario, we need to proceed to establish a record of accomplishment and demonstrated capability. This is already occurring in terms of the evolution from low to higher power arcjets. The demonstration of higher power capabilities has four benchmarks still to achieve: efficiency, specific impulse, high power operation, and lifetime.
- We will not achieve these benchmarks, in a reasonable time, even in a minimal way commensurate with the budget, unless the following tasks are accomplished:
  1. Increase the discharge voltage relative to the electrode voltages.
  2. Control the plasma flow in terms of both its behavior within the accelerator, and its outward direction.
  3. Demonstrate at all levels of power appropriate to SEI, so that we are recognized as a continuing player. Such demonstration clearly has to become more faithful to the system environment as the mission application draws near.
  4. Demonstrate as much as we can, within budget limitations, so that at least lifetime questions on critical components can be answered. We fired rocket engines into atmosphere, and gained knowledge about combustion instabilities in large engines, long before we were able to test at altitude.

## RESEARCH STRATEGIES

SHOULD THE PROGRAM BE BIFURCATED ?

"To  $\bar{B}$ , or not to  $\bar{B}$  ?"

- Bob Jahn, 1965

ARE THERE TECHNICAL REASONS THAT PRECLUDE COMMONALITY BETWEEN LOW AND HIGH POWER MPD ARCJETS ?

- Easy answer: Yes. The lower power arcjets have too much of their energy economy tied up in electrode losses to be relevant to high power devices for which such losses, in principle, are negligible. To the extent that a variety of instabilities, not to mention mass addition phenomena, depend on energy available in non-directed forms, even basic behavior may vary substantially from sub-megawatt to multi-megawatt operation.
- More challenging answer: No. To find application in near term missions, the lower power thrusters must become more efficient. This requires that the relative electrode voltages become small in low power devices. Apart from reducing the electrode voltages by inventing better arrangements, we must increase the discharge voltage. This demands that the discharge operate properly at lower currents, which directs our attention to conditions that determine discharge uniformity. Such conditions, and their relation to physical scale sizes, may be commensurate across the total operating range of interest. (For example, critical wavelength vs distance along current flow direction.)

Furthermore, it may be appropriate for all MPD thrusters to incorporate magnetic nozzles for improved thrust efficiency. Thus, the presence of applied magnetic field components becomes a matter of degree and optimization.

## MPD THRUSTER RESEARCH AND DEVELOPMENT

### SUMMARY

#### ACTIVITIES AND PLANS IN THE OSU AAE DEPARTMENT

-- Experimental and theoretical research on

magnetic nozzles at present and higher power levels;

MPD thrusters with applied fields extending into the thrust chamber;

improved electrode performance (e.g., hollow cathode)

-- Tools

MACH2 code for MPD and nozzle flow calculation;

Laser diagnostics and spectroscopy for non-intrusive measurements of flow conditions (e.g., particle temperatures, fluctuations);

Extension to higher power (Godzilla, burst-mode arcjet at OSU, and cooperative experiments at NASA LeRC).

#### NATIONAL STRATEGIES

-- Make the next steps beyond the experimental and theoretical base to demonstrate improved performance based on optimizing geometry for terminal values. Numerical modeling with validated code(s) is critical here.

-- Demonstrate whatever we can across the full spectrum of SEI mission interest to be a major and continuing player. Allow fidelity for full system life test to be modulated by mission immediacy and dollars. Test component lifetimes to support development efforts and system studies.